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Strain response analysis of adhesively bonded extended composite wind turbine blade suffering unsteady aerodynamic loads

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ABSTRACT

Extending blades of wind turbine in service is the most effective method for increasing energy production. Adhesively bonding technology increases less mass and has simpler operation process, which is more suitable for extending blades in service. But unsteady aerodynamic loads on the blades due to stochastic turbulent inflow may lead to fatigue damage and even failure. This paper presented a study on strain response and fatigue life of adhesively bonded extended composite wind turbine blade suffering unsteady aerodynamic loads. Firstly, a loading method that applies periodic distributed aerodynamic loads on the blade was proposed to accurately simulate the unsteady distributed loads on the real extended blades in service. Secondly, strain response behaviors to unsteady aerodynamic loads and strain distribution behaviors in the adhesively bonded area were revealed. Finally, fatigue damage was predicted with unsteady aerodynamic load spectrums, rainflow cycle-counting algorithm, Goodman diagram and Miner's linear superposition principle. Based on the findings obtained from this study, the feasibility of adhesively bonding technology for extending blade was affirmed and a few potential future directions of study were addressed to reduce the risk of adhesively bonded structures.

1. Introduction

Increasing the energy production or reducing the maintenance costs is the main way to improve the economy of wind turbines in service. In the wind turbine system, the blades are one of the most critical components to capture the power from wind. It has been well known that [1] the power output is proportional to swept area and wind speed cubed. Therefore, extending blades is one of the most effective method to harvest more wind energy in low wind speed region.

Generally, there are two method to extend the wind turbine blades in service, metal bolt connection [2–4] and adhesively bonded connection [5–7]. Compared with metal bolt connection, adhesively bonded connection method has better fatigue behaviors and simpler operation process, and increases less mass, which is more suitable for the connection of composite shell structures and is discussed in this paper.

Wind turbine rotors usually run in the nature atmospheric boundary layer. The stochastic turbulent inflow would induce unsteady aerodynamic loads [8,9], which are the primary source of fatigue loads in flapwise direction. How to make sure that the adhesively bonded extended composite wind turbine blade can endure the long-term unsteady aerodynamic loads?

Usually, fatigue testing is conducted to verify a blade's ability to withstand its operating load spectrum over a design life of

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20 years [10]. The real operating load spectrum consists of more than 10^9 stochastic load cycles due to irregular turbulent inflow [11]. So the load spectrum is compressed into an equivalent fatigue load history of 10^6–10^7 cycles that can be applied in no more than a few months using linear damage principles [12–14]. The equivalent fatigue loads can be applied with hydraulic actuators or resonant eccentric mass [11] installed at one or several locations along the blade. However, Svensson [15] found that the fatigue load variation is an important source of scatter among material variability and other uncertainties. Lange [16] also found that fatigue reliability to be significantly affected by the type of model chosen for the loads data. The hydraulic actuators or resonant eccentric mass methods can only apply concentrated loads, which are clearly different from the distributed loads induced by flow over blades.

The purpose of this work is to understand the structural response and predict fatigue damage of adhesively bonded area for extended blades suffering unsteady aerodynamic loads. An experimental method that the distributed aerodynamic loads are applied with a rotating apparatus to the extended blades was proposed and validated by computational fluid dynamics (CFD) method firstly. Secondly, strain response to pitching angle and rotating speed was analyzed, and then the distribution behaviors in the adhesively bonded area were studied. Finally, fatigue damage of adhesively bonded area for extended blades was predicted with unsteady aerodynamic load spectrums, rainflow cycle-counting algorithm [17], Goodman diagram [18] and Miner's linear superposition principle [19].

2. Experiment setup

It has been known that the turbulent inflow in the nature atmospheric boundary layer would induce unsteady aerodynamic loads. In essence, the unsteady loads are resulted from the time-variant inflow angle and speed. In this experimental investigation, a rotating apparatus was designed and ran with pitch angle and rotating speed changed in a control law to simulate the turbulent inflow conditions and generate periodic aerodynamic loads. An adhesively bonded extended blade with length of 3.5 m was designed, manufactured and tested.

2.1. Rotating experimental apparatus

It is high cost to build a horizontal axis rotating apparatus for the same rotor diameter, which needs a tower and more room for the indoor test. A rotorcraft-like apparatus was designed and installed on the foundation of laboratory, as shown in Fig. 1. The weight of total apparatus without blades is about 1450 kg and the height at hub center is 1809 mm. When the 3.5 m length blades are mounted on the hub, rotor diameter will be 7674 mm.

Rotating motion is driven by a 22 kW AC motor and a gearbox with ratio of 10.41. The rotating speed can be controlled by a frequency converter, and the rated output speed is 150 rpm. The rotating azimuth angle is recorded by a 12-bit encoder with resolution of 0.088°. Pitching motions of two blades are synchronously driven by a servo motor mounted on the hub with a pair of

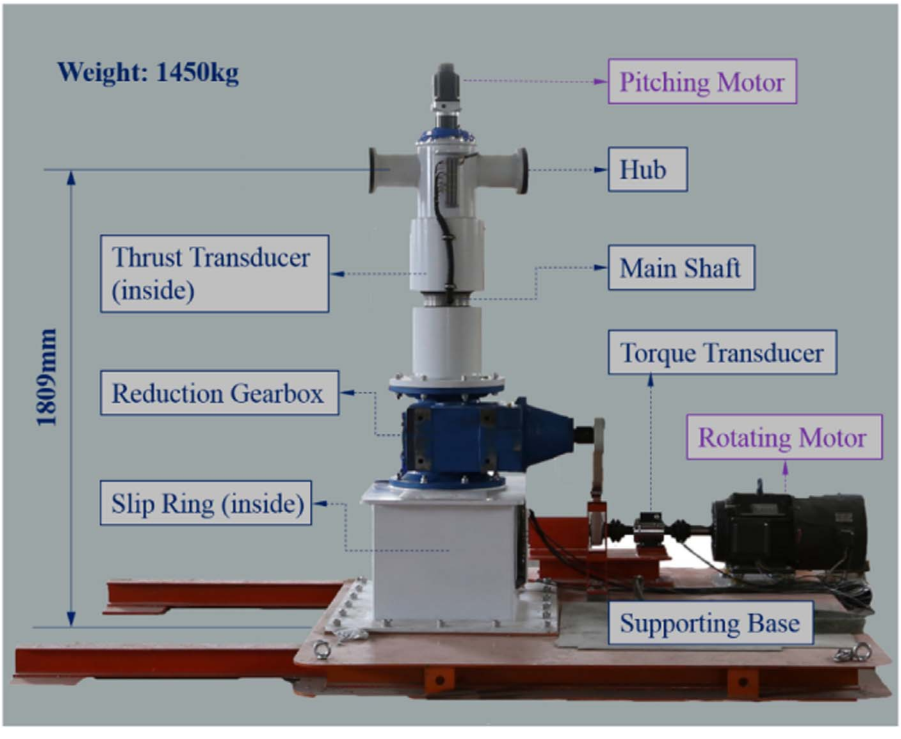

Fig. 1. The components of rotating experimental apparatus.